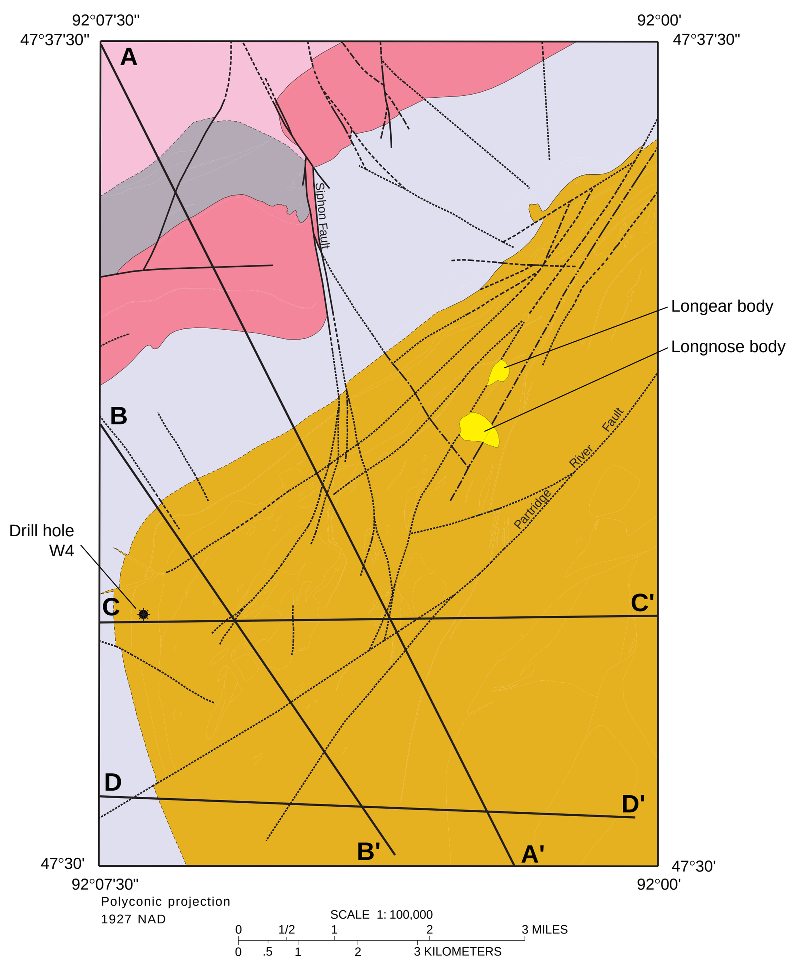
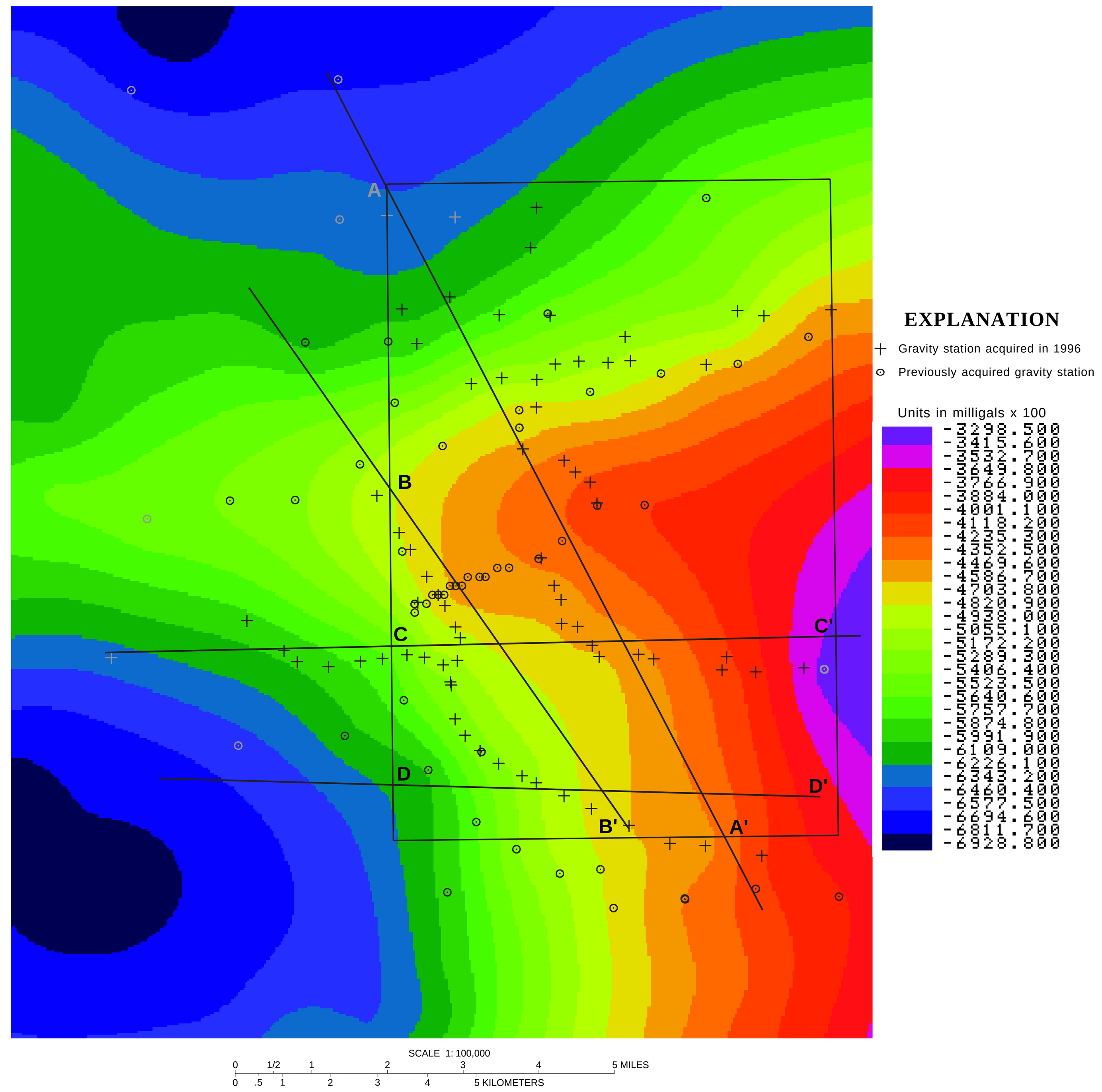
SUPPORTED BY THE MINNESOTA MINERALS DIVERSIFICATION PROGRAM
AS ADMINISTERED BY THE MINERALS COORDINATING COMMITTEE FOR THE MINNESOTA LEGISLATURE

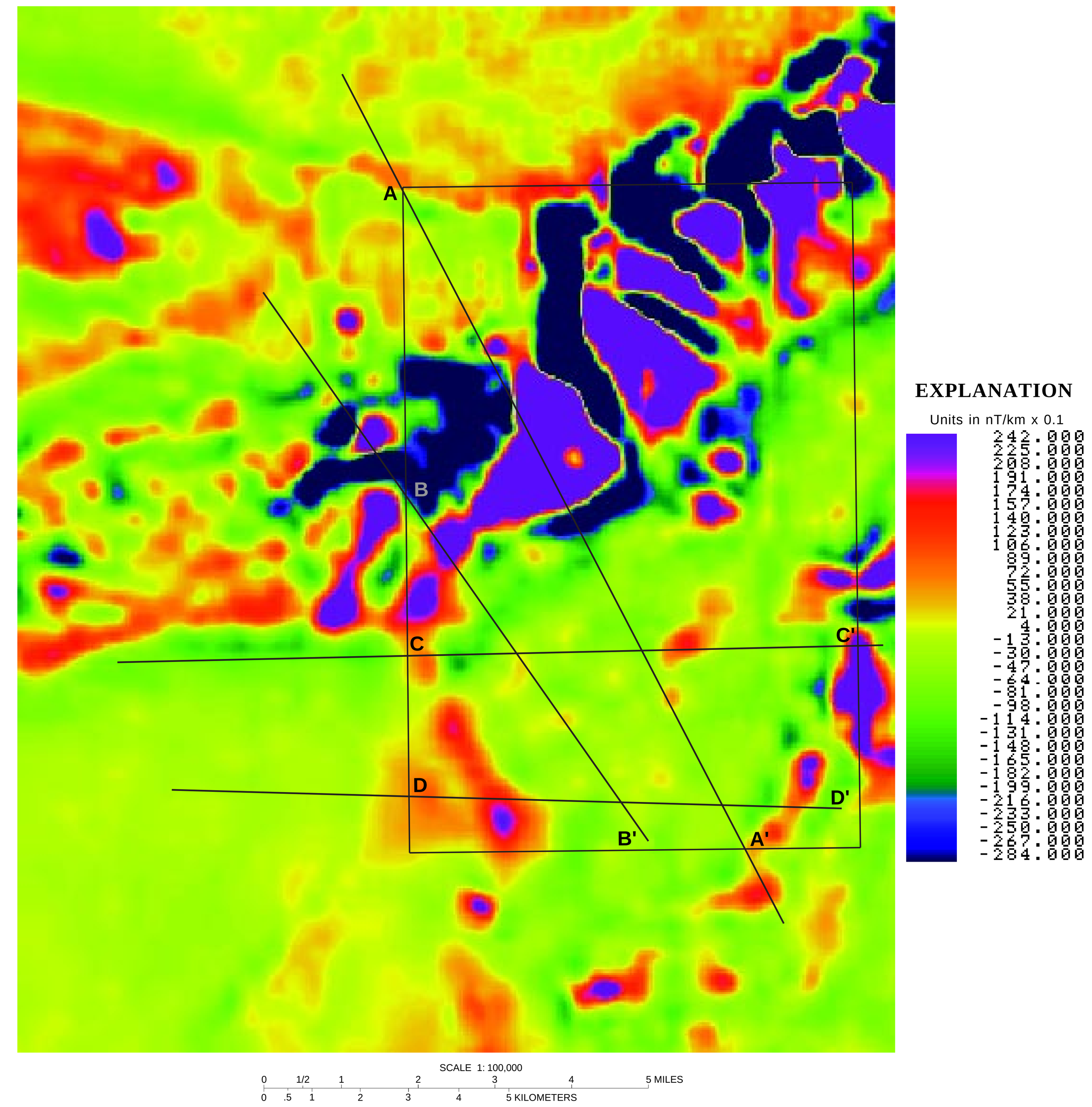


Simplified Bedrock Geologic Map of the Allen 7.5-Minute Quadrangle

(Modified from Severson and Miller, in press)



Bouguer Gravity Anomaly Map of the Allen 7.5-Minute Quadrangle and Adjacent Areas Showing Gravity Stations and Lines of Profile



Magnetic Anomaly Map (First Vertical Derivative) of the Allen 7.5-Minute Quadrangle and Adjacent Areas Showing Lines of Profile

EXPLANATION OF SIMPLIFIED GEOLOGIC MAP AND PROFILES

(Modified from Severson and Miller, in press)

GEOLOGIC UNITS

Duluth Complex, undivided (Mesoproterozoic)—Stipple (on profiles only) indicates dense magnetic units in the upper part of the Complex.

Oxide ultramafic intrusions—Specifically, the Longnose and Longear intrusions. Shown only on map,

Virginia Formation (Paleoproterozoic).

Biwabik Iron Formation (Paleoproterozoic).

Granitic rocks (Archean).

Metasedimentary rocks (Archean).

Metavolcanic rocks (Archean)—Shown only on profiles.

Drill hole used to define the drop-off in profile C–C'—Shown only on map.

MEASUREMENTS AND SYMBOLS ON PROFILES

Some of the models extend beyond the edge of the Allen quadrangle as shown by the lines of profile on the geophysical maps. This was done to improve the reliability of the models away from the base of the Complex, but only those segments of the models within the Allen quadrangle are shown on the profiles.

All models assume an Earth field having an intensity of 59,000 nanoTeslas and a declination/inclination of 2°/75°. The numbers on model geologic units indicate the following:

2.70 **Density**—Grams per cubic centimeter (gm/cc).

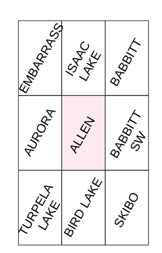
0.02330 **Magnetic susceptibility**—Centimeter-gram-second (cgs).

0.00100 **Intensity of natural remanent magnetization (NRM)**—Centimeter-gram-second (cgs).

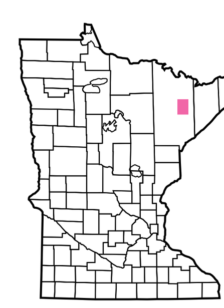
288°/50° **Declination/inclination of natural remanent magnetization (NRM).**

○ **Measured data.**

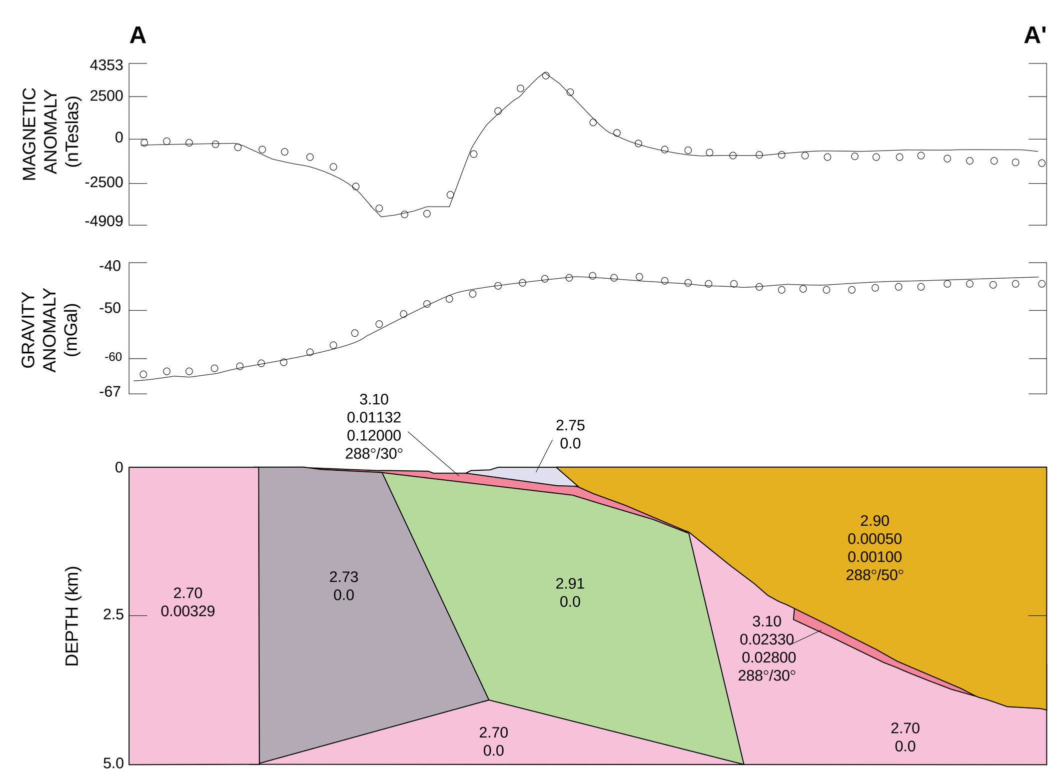
Model data.

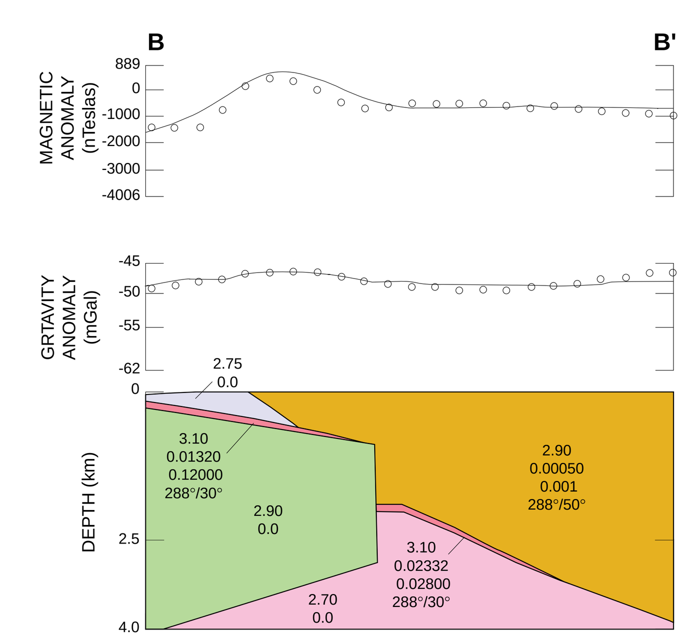


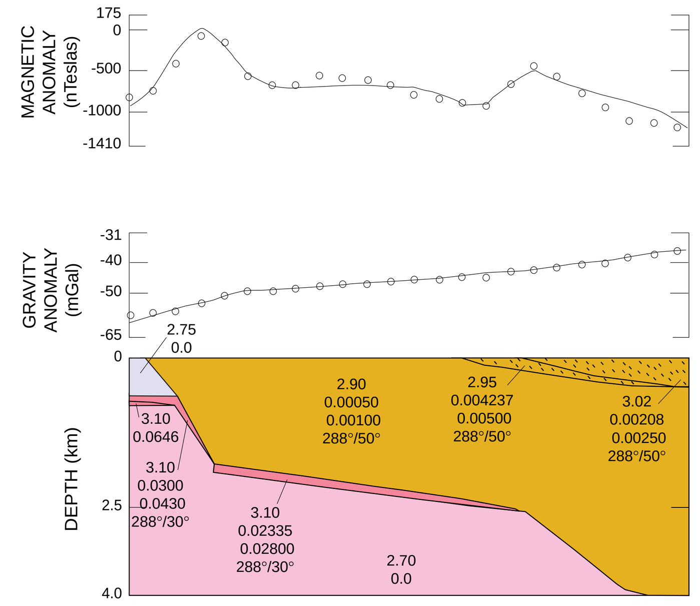
INDEX TO 7.5-MINUTE QUADRANGLES



QUADRANGLE LOCATION

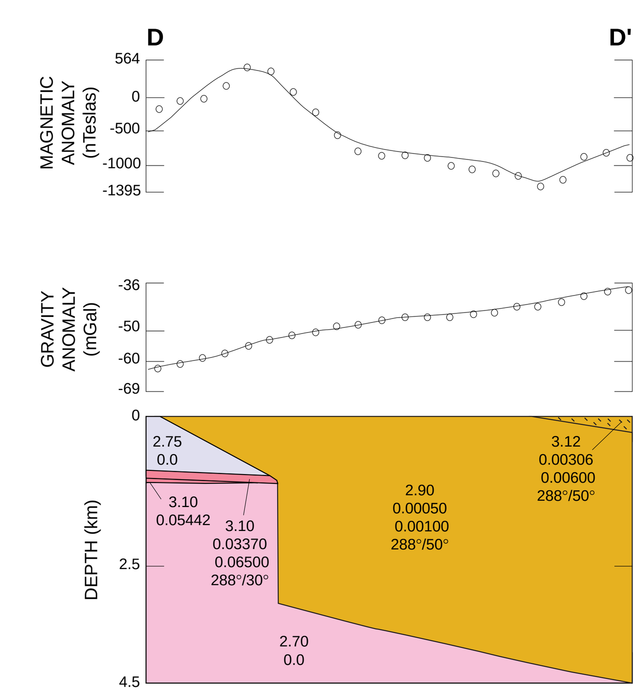






SCALE 1:100,000

The model profiles use original magnetic anomaly values, not the first vertical derivative.



GRAVITY AND MAGNETIC MODELING OF THE DULUTH COMPLEX IN THE ALLEN 7.5-MINUTE QUADRANGLE, ST. LOUIS COUNTY, MINNESOTA

By

V.W. Chandler and R.S. Lively

1998

INTRODUCTION

To compliment geologic mapping of the Allen 7.5-minute quadrangle in northeastern Minnesota (Severson and Miller, in press), gravity and magnetic modeling was conducted to investigate geology at depth. Of particular interest is the Mesoproterozoic Duluth Complex, which in this area chiefly consists of troctolitic rocks having minor amounts of ultramafic, gabbroic, anorthositic, and volcanic rocks. In the Allen quadrangle, the Duluth Complex is emplaced in the Paleoproterozoic Animikie sequence, which consists of the Virginia Formation higher in the section and the Biwabik Iron Formation near the base (see the simplified geologic map). The sequence dips gently to the south and southeast and rests on Archean basement composed of metasedimentary, metavolcanic, and granitic rocks. The strike of the basal contact of the Duluth Complex abruptly changes from a northeast strike to the north, to a north–south strike to the south. The change in strike appears to mark a major structural transition, because previous geologic studies (for example, Bonnichsen, 1972) and geophysical studies (for example, Chandler and Ferderer, 1989) imply that the basal contact of the Complex commonly has gentle to moderate dips to the northeast of the Allen quadrangle and steep dips to the south. The primary objective of the modeling was to investigate the subsurface structure of the basal contact at this apparent zone of transition.

PREVIOUS GEOPHYSICAL STUDIES IN THE ALLEN QUADRANGLE

This project included a review of case histories of exploration efforts in the state by various private companies. The files are maintained at the Minnesota Department of Natural Resources (DNR) Library in Hibbing. Minnesota. Unfortunately, most of the geophysical data in these files yielded relatively little information regarding the structure of the Complex at depth. Scattered seismic-refraction lines acquired by New Jersey Zinc (Tps. 58 and 59 N. and Rs.13 and 14 W. Refer to U.S. Geological Survey topographic maps for Township, Range and Section locations.) indicate that the glacial overburden is 0–30 meters (m) thick. The Allen quadrangle lies within an area in which Bear Creek Mining, New Jersey Zinc, and Kawishiwi Land conducted airborne electromagnetic (EM) surveys. Conductors are abundant over parts of the Virginia Formation and Biwabik Iron Formation, but with the exceptions of the Longear and Longnose deposits (see the simplified geologic map), conductors are sparse over this part of the Duluth Complex. A magnetic and induced-polarization (IP) survey by Cleveland Cliffs revealed two northeast-striking IP anomalies that lie outside the Complex in the southwest quarter of sec. 16, T. 58 N., R. 14 W. A short, detailed gravity profile was acquired by Humble Oil along an east–west line, the midpoint of which was near the southwest corner of sec. 15, T. 58 N., R. 14 W. The observed gradient of greater than 3 milligals per kilometer (mg/km) implies proximity to the basal contact. Detailed gravity, electromagnetic, magnetic, and seismic data were acquired by New Jersey Zinc and American Shield over the Longear and Longnose deposits in secs. 19 and 30, respectively, of T. 59 N., R 13 W. Both deposits are associated with pronounced gravity, electromagnetic, and magnetic anomaly signatures. Modeling of the Longear and Longnose gravity anomaly signatures, which have magnitudes of 2–3 mg, imply the presence of a tabular mass that has a thickness of 150 m, a density contrast of 0.7 grams per cubic centimeter (gm/cc), and contacts that dip steeply southeast. Unfortunately, neither the Humble Oil nor the New Jersey Zinc and American Shield gravity data are sufficiently documented to allow a tie-in with the gravity data of this study.

The Allen quadrangle lies within the area of a gravity and magnetic study of the western Duluth Complex conducted by Allan Spector and Associates (1995). A gravity-model profile from that study (5–5') is adjacent to geologic profile B–B' of the present study (discussed below). The interpretation of the Spector profile differs considerably from that of geologic section B–B'. It infers a maximum thickness of only 1.5 km for the Complex, as well as a 3-km-wide, 150-m-thick basin of overburden centered roughly 5 km inside the Complex. Although Spector and Associates inferred the presence of the overburden basin from magnetic depth estimating methods, this interpretation is vitiated by the presence of outcropping gabbroic rock in the area of supposed thick overburden (Severson and Miller, in press). A probable factor in the discrepancy between the gravity interpretations of Spector and Associates and of this study is that the latter is based on considerably improved gravity coverage.

PREPARATION OF GRAVITY AND MAGNETIC MODELS

This study utilizes previously existing gravity coverage (Ikola, 1968; Chandler and Schaap, 1991), and 73 new stations that were acquired in 1996 (see the Bouguer gravity anomaly map). The data were reduced to Bouguer anomaly values using standard techniques. Considering positional and elevation uncertainties, as well as repeat observations at selected stations, the maximum error in Bouguer gravity values is estimated to be +/- 0.4 mg. The magnetic data are from a statewide program of aeromagnetic surveying (Chandler, 1991), which was conducted in this area along north–south flight lines that were flown 400 m apart and 150 m above ground level. Gravity and magnetic profiles used for the models were interpolated at a 400-m interval from gravity and aeromagnetic data using U.S. Geological Survey programs MINC, PROFGRD, and PROF2SAK (Cordell and others, 1992). To maintain details in gravity signatures, profiles were positioned to lie along corridors of relatively closely spaced measurements (see the gravity anomaly map). The gravity and magnetic modeling is based on U.S. Geological Survey program SAKI, which assumes two-dimensional (strike-infinite) sources, although end corrections are applied to approximate three-dimensional modeling. To enhance several anomaly features to be discussed below, a first-vertical-derivative operation was performed on the magnetic data (see the magnetic anomaly map) using U.S. Geological Survey program FFTFIL (Cordell and others, 1992).

Wherever possible, modeling was constrained by outcrop and drill-hole data (Severson, 1988; Severson and Miller, in press) and associated rock-property data. Density and magnetization values were selected to be consistent with previously reported values, which were derived through rock-property measurements (Chandler, 1990) or modeling (Bath, 1962; Chandler and Ferderer, 1989). These studies indicate that the Duluth Complex rocks, as well as the Biwabik Iron Formation near the basal contact, carry a strong natural remanent magnetization that is directed downward at a moderate angle toward the west. Additional density and magnetic-susceptibility data were acquired from hand and core samples during the geologic mapping of the Allen quadrangle (V.W. Chandler, unpubl. data, 1998). Modeling of the basal contact to depths of 0.5–1.0 km was constrained by exploration drill holes (Severson, 1988). These drill-hole data as used for subsurface control are reasonably good along profiles B–B' and C–C', and poor along profiles A–A' and D–D'. Models of the up-dip parts of the Duluth Complex are largely based on the Biwabik Iron Formation, the down-dip extensions of which, beneath the Duluth Complex, are associated with extremely strong magnetic signatures. Models of the deeper parts of the Complex are largely based on the observed gravity signature. To ensure reliable modeling of the long-wavelength anomaly components, the original model profiles were extended beyond the Allen quadrangle, as shown on the magnetic and gravity maps, although only the segments within the quadrangle are shown on the profiles. The models were also constructed to agree at their points of intersection.

INTERPRETATION OF RESULTS

The positive gravity signature of the Duluth Complex along profiles A–A' and B–B' is complicated by a gravity high that is attributed to a dense (2.90–2.91 gm/cc) mass of Archean metavolcanic rocks, that is 3–5-km thick. In the Allen quadrangle, these metavolcanic rocks are overlain by Animikie strata, but the associated gravity high extends 10 km to the west (see the gravity anomaly map), where metavolcanic rocks are exposed (Jirsa and others, 1998). Because of a lack of density contrast, gravity modeling of the basal contact of the Duluth Complex where it overlies metavolcanic rocks is ambiguous, but some definition is still possible through magnetic modeling of the Biwabik Iron Formation, which commonly lies between the two units (see profiles A–A' and B–B'). At the north end of profile A–A', the 3–5-km-thick mass of moderate density (2.73 gm/cc), nonmagnetic material correlates with exposures of metasedimentary rocks, whereas the low-density (2.70 gm/cc), strongly magnetic (susceptibility equals 0.00329 centimeter-gram-second or cgs) mass to the north correlates with Archean granitic rocks.

The magnetic models are dominated by the Biwabik Iron Formation. As pointed out by Bath (1962), the strong natural remanent magnetization overprint on the iron-formation produces a magnetic signature that places intense lows approximately over its outcrops, and intense highs approximately over its down-dip truncation by the Duluth Complex. To help match the high at the west end of profile C–C', the iron-formation was partly extended down the steep drop-off that is interpreted to represent faulting. This extension may represent slivers of iron-formation caught between several down-dropping faults or a drooping mass of oxide-rich intrusive rocks that was created by the interaction of iron-formation and troctolitic magma. A deeply buried outlier of iron-formation is inferred along the floor of the Complex on profiles A–A', B–B', and C–C'. This poorly constrained outlier was included primarily to accommodate a broad magnetic high on profile C–C'. Beyond the Complex on profiles C–C' and D–D', a westward-thickening wedge of iron-formation that lacks natural remanent magnetization most likely represents its gradual decrease away from the thermal aureole of the contact.

The models imply that the basal contact of the Duluth Complex typically dips 25°–45°. Abrupt thickening of the Complex to the south and southeast on profiles B–B', C–C', and D–D' implies that the basal contact has been broken by large-scale faulting. The presence of the fault as shown on C–C' is supported by nearby drill-hole W-4 (see the simplified geologic map), which, despite its proximity to the exposed basal contact, penetrated more than 949 m of troctolitic rocks without encountering footwall rock (Severson, 1988). These inferred faults do not appear to be directly related to structures mapped at the bedrock surface, but the north–northwest-striking fault defined by the drop-offs modeled along profiles C–C' and D–D' is subparallel to minor faults that cut the basal contact (see the simplified geologic map) and Paleoproterozoic and Archean rocks to the north and northwest (G.B. Morey, oral commun., 1998). The combined models imply that the Duluth Complex progressively thickens to the southeast and east to a thickness of 4.5 km beneath the southeastern part of the Allen quadrangle.

The gravity and magnetic modeling permit the formulation of a structural model for this part of the Duluth Complex. The moderate dips along the northeast-striking part of the basal contact (profile A–A', as well as regions to the northeast) may be caused by sagging, or by a series of minor northeast-striking tensional faults that form a step-and-riser geometry along the floor of the Complex (Weiblen and Morey, 1980; Chandler and Ferderer, 1989). To the southwest, much of this southeast-downward displacement may have concentrated along a single fault zone (the drop-off in model B–B'). The southeast-downward displacement is abruptly truncated along an apparent tear fault that corresponds to the north–northwest-striking drop-off defined on profiles C–C' and D–D'. This fault can be traced to the south along the north–northwest striking magnetic high in the southwestern corner of the Allen quadrangle (see the derivative magnetic anomaly map), which is interpreted to reflect the subsurface truncation of the Biwabik Iron Formation by faulting. Magnetic highs immediately south of the Allen quadrangle imply that the strike of faulting switches abruptly to the northeast, perhaps reflecting a tensional segment, then back to a north–northwest strike, perhaps reflecting another tear fault (see the derivative magnetic anomaly map). The timing of the faulting is unknown, but it is inferred here to be co-magmatic, perhaps occurring during the main phase of emplacement of the upper part of the Partridge River troctolite (Severson and Miller, in press). A series of northwest-striking tensional faults and north–northwest-striking tear faults within and to the south of the Allen quadrangle may explain the general north–south strike of the basal contact zone of the southern Duluth Complex, as well as its interpreted steep dips (Chandler and Ferderer, 1989).

ACKNOWLEDGMENTS

The authors thank Allen Strandlie and Ben Verbick of LTV Steel and William Harrison and Joel Reed of the Duluth Misabe and Iron Range Railroad for granting permission to enter their properties, and for generously providing elevation data. Larry Zanko of the Natural Resources Research Institute provided additional elevation control using Global Positioning System (GPS) surveying. Steve Hauck provided magnetic susceptibility data from drill core. Tim Wahl and Matt Benson of the Minnesota Geological Survey assisted in computer compilation and rock-property measurements, respectively.

REFERENCES CITED

Bath, G.D., 1962, Magnetic anomalies and magnetizations of the Biwabik iron-formation, Mesabi area, Minnesota: Geophysics, v. 27, no. 5, p. 267–650.

Bonnichsen, Bill, 1972, Southern part of Duluth Complex, *in* Sims, P.K., and Morey, G.B., eds. Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 361–87.

Chandler V.W., 1990, Geologic interpretation of gravity and magnetic data over the central part of the Duluth Complex, northeastern Minnesota: Economic Geology, v. 85, p. 816–829.

———1991, Aeromagnetic anomaly map of Minnesota: Minnesota Geological Survey State Series Map S-17, scale 1:500,000.

Chandler, V.W., and Ferderer, R.J., 1989, Copper nickel mineralization of the Duluth Complex, Minnesota—a gravity and magnetic perspective: Economic Geology, v. 84, p. 1690–1696.

Chandler V.W. and Schaap B.D., 1991, Bouguer gravity anomaly map of Minnesota: Minnesota Geological Survey State Series Map S-16, scale 1:500,000.

Cordell, L., Phillips, J.D., and Godson R.H., 1992, U.S. Geological Survey potential-field geophysical software version 2.0: U.S. Geological Survey Open-File Report 92-18.

Ikola R.J., 1968, Simple Bouguer gravity map of the southern part of the Duluth Complex and adjacent areas, Minnesota: Minnesota Geological Survey Miscellaneous Map Series Map M-4, scale 1:125,000.

Jirsa, M.A., Boerboom, T.J., and Morey, G.B., 1998, Bedrock geologic map of the Virginia Horn, Mesabi iron range, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series Map M-85, scale 1:48,000.

Severson, M.J., 1988, Geology and structure of a portion of the Partridge River intrusion: A progress report: University of Minnesota Natural Resources Research Institute Technical Report NR/GMIN-TR-88-08, 78 p.

Severson, M.J., and Miller, J.D., in press, Geology of the Allen quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-91, scale 1:24,000.

Spector, A., and Associates, 1995, Report on Aeromagnetic data interpretation, western Duluth Complex for the Minnesota Department of Natural Resources: Minnesota Department of Natural Resources, Division of Minerals open-file report, 15 p.

Weiblen, P.W, and Morey, G.B., 1980, A summary of the stratigraphy, petrology and structure of the Duluth Complex: American Journal of Science, v. 280, p. 88–133.